METHOD AND SYSTEM FOR ENHANCED RESOLUTION, AUTOMATICALLY-CALIBRATED POSITION SENSOR

CROSS REFERENCE TO RELATED APPLICATIONS

The present invention claims priority from U.S. Provisional Application Serial No. 60/523,648, filed November 20, 2003, entitled "Method, System, and Computer Program for Enhanced Resolution, Automatically-Calibrated Magnetic Position Sensor," which is hereby incorporated by reference herein in its entirety.

BACKGROUND OF THE INVENTION

Sensors for detecting position and displacement are often used in many mechanical processes in which it is important to position and/or move a ram, or the like, axially under precise control. It is well known in the art that signals containing information related to the position and displacement of a moving ram can be generated by mounting transducers in close proximity to the ram and outfitting the ram with equally-spaced magnetic bands disposed circumferentially around the girth of the ram. It is common for such systems to employ two transducers mounted in close proximity to the ram such that when the ram moves, the bands of magnetic material pass by the transducers thereby generating sinusoidal output voltages at the transducers. Traditionally, the two transducers are positioned precisely in respect to each other such that the two sinusoidal output signals are in quadrature (i.e., the transducer output signals are 90 degrees out of phase). Conversion of the two sinusoidal signals in quadrature into corresponding digital pulse trains, wherein each pulse corresponds to the passage of a magnetic band, yields meaningful information related to the position and displacement of the ram. Each pulse train changes state twice, once for each time the corresponding sinusoidal output signal crosses zero, over one period from one magnetic band to the next. Due to the fact that the pulse trains are 90 degrees out of phase, four state changes occur per period. It is well known in the art that the pattern of the state changes of the pulse trains reveals information related to the position and displacement of the ram. However, because there are only four discernible state changes per period, the resolution of such systems is limited and often proves inadequate.

Numerous systems and techniques for enhancing the resolution of conventional quadrature position and displacement sensors are known. However, these systems and techniques are plagued by a number of infirmities. For instance, many known systems for enhancing resolution require long chains of costly analog electronic circuitry. In addition to increasing cost, the elaborate analog circuitry required by such systems increases the systems' sensitivity to electromagnetic noise, distortion, and other environmental disturbances. Furthermore, many known systems for enhancing resolution often require the size and the complexity of the circuitry to scale proportionately with the desired increase in resolution. In other words, in order to double the resolution of the system, it is necessary to double the size and complexity of the circuitry. Moreover, a number of known systems for enhancing resolution cannot handle changes in the amplitude of the transducer output signals and consequently require manual calibration of analog circuit components like potentiometers. Finally, numerous known systems rely on lengthy, difficult, and costly digital operations such as digital division operations.

There is therefore a need in the art for a simple and efficient method and system of sensing the position and displacement of a moving substrate, ram or the like that provides, among other things, enhanced resolution and is capable of self-calibration.

BRIEF SUMMARY OF THE INVENTION

According to one aspect of the invention, a system for sensing position and/or displacement of a moving ram, substrate, target, piston or optical encoder is provided in which multiple state changes are generated in two quadrature signals, such that the state changes correspond to discreet locations within the interval between two magnetic bands or respective apertures of an optical encoder wheel, for example.

In accordance with this aspect of an embodiment of the invention, the ram, substrate, piston, or target is outfitted with a plurality of equally-spaced bands of magnetic material disposed circumferentially around the girth of the ram or place as required or desired, or alternatively apertures are provided on an optical wheel or the like. Further in accordance with this aspect of the invention, a first signal acquisition means for acquiring a first signal related to the position of the ram and a second signal acquisition means for acquiring a second signal related to the position of the ram that is 90 degrees out of phase with the first signal related to the position of the ram is provided. Still further in accordance with this

aspect of the invention, a signal selection means is provided for comparing the first signal related to the position of the ram and the second signal related to the position of the ram, selecting the signal with the lesser instantaneous magnitude as the primary signal, selecting the signal with the greater instantaneous magnitude as the secondary signal, and producing a reference signal indicating whether the first signal related to the position of the ram or the second signal related to the position of the ram was selected as the primary signal. Yet further in accordance with this aspect of the invention, a phase angle converter means is provided for converting the primary signal into a phase angle signal. Still further in accordance with this aspect of the invention, an angular movement detection means is provided for determining angular movement over time based on the value of the phase angle signal over time.

Yet further in accordance with this aspect of an embodiment of the invention, the phase angle converter means includes a signal normalizing means for producing a normalized position signal by mapping the primary signal to a corresponding signal with a known amplitude; a phase angle lookup means for converting the normalized position signal into an uncorrected phase angle signal corresponding to the instantaneous phase angle of the normalized position signal; and a phase translation means for producing a phase angle signal by correcting the phase angle signal based on the values of the secondary signal and the reference signal.

Still further in accordance with an aspect of an embodiment of the invention, the angular movement detection means includes a phase register means for storing the phase angle signal and outputting a previous iteration phase angle signal equal to the phase angle signal and a phase subtractor means for producing an uncorrected angular movement signal by subtracting the previous iteration phase angle signal from the phase angle signal. Yet further in accordance with this aspect of the invention, the angular movement detection means also includes an overflow corrector means for correcting the uncorrected angular movement signal in the case of an overflow or underflow and producing the angular movement signal.

Still further in accordance with an aspect of an embodiment of the invention, the first signal acquisition means includes a first transducer and a second transducer mounted in close proximity to the ram such that when the ram moves the plurality of bands of magnetic material disposed circumferentially around the girth of the ram pass the transducers and

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thereby generate sinusoidal output signals at each transducer. Yet further in accordance with this aspect of the invention, the two transducers are positioned linearly with respect to each other and are spaced such that the distance between the first transducer and the second transducer is one-half of the distance between two adjacent bands of magnetic material disposed circumferentially around the girth of the ram. Consequently, the first transducer output signal is 180 degrees out of phase with the second transducer output signal.

Still further in accordance with an aspect of an embodiment of the invention, the second signal acquisition means includes a third transducer and a fourth transducer mounted in close proximity to the ram such that when the ram moves the plurality of bands of magnetic material disposed circumferentially around the girth of the ram pass the transducers and thereby generate sinusoidal output signals at each transducer. Yet further in accordance with this aspect of the invention, the two transducers are positioned linearly with respect to each other and are spaced such that the distance between the third transducer and the fourth transducer is one-half of the distance between two adjacent bands of magnetic material disposed circumferentially around the girth of the ram. Consequently, the third transducer output signal is 180 degrees out of phase with the fourth transducer output signal. Still further in accordance with this aspect of the invention, the third transducer is located between the first transducer and the second transducer, and the distance between the third transducer and the first transducer and the distance between the third transducer and the second transducer is one-quarter of the distance between two adjacent bands of magnetic material disposed circumferentially around the girth of the ram. Yet further in accordance with this aspect of the invention, the distance between the fourth transducer and the first transducer is three-quarters of the distance between two adjacent bands of magnetic material disposed circumferentially around the girth of the ram, and the distance between the fourth transducer and the second transducer is one-quarter of the distance between two of the adjacent bands of magnetic material disposed circumferentially around the girth of the ram.

Still further in accordance with an aspect of an embodiment of the invention, the first signal acquisition means also includes a first signal combining means for producing a first combined signal by subtracting the second transducer output signal from the first transducer output signal and amplifying the resulting signal; a first analog-to-digital converter for producing the first signal related to the position of the ram by converting a first calibrated signal into a digital signal; a first averaging means for producing a first digital error signal by

performing a time-average of the first signal related to the position of the ram and subtracting the time-average of the first signal related to the position of the ram from the value of the direct current offset required by the first analog-to-digital converter; a first digital-to-analog converter for converting the first digital error signal into a first analog error signal; and a first subtractor means for producing the first calibrated signal by subtracting the first analog error signal from the first combined signal.

Yet further in accordance with an aspect of an embodiment of the invention, the second signal acquisition means also includes a second signal combining means for producing a second combined signal by subtracting the fourth transducer output signal from the third transducer output signal and amplifying the resulting signal; a second analog-to-digital converter for producing the second signal related to the position of the ram by converting a second calibrated signal into a corresponding digital signal; a second averaging means for producing a second digital error signal by performing a time-average of the second signal related to the position of the ram and subtracting the time-average of the second signal related to the position of the ram from the value of the direct current offset required by the second analog-to-digital converter; a second digital-to-analog converter for converting the second digital error signal into a second analog error signal; and a second subtractor means for producing the second calibrated signal by subtracting the second analog error signal from the second combined signal.

Still further in accordance with an aspect of an embodiment of the invention, the first signal combining means and the second signal combining means are differential amplifiers.

Yet further in accordance with an aspect of an embodiment of this invention, a traditional quadrature output emulating means is provided for converting the angular movement signal into traditional quadrature output signals.

Still further in accordance with an aspect of an embodiment of the invention the signal normalizing means computes the amplitude of the primary signal, and maps the primary signal to a corresponding sinusoidal signal with known amplitude. Yet further in accordance with this aspect of the invention, the calculation of the amplitude of the primary signal and the mapping of the primary signal to a corresponding signal with known amplitude is facilitated by the use of a lookup table.

Still further in accordance with an aspect of an embodiment of the invention, the phase angle lookup means determines the instantaneous phase angle of the normalized position signal using a lookup table.

Yet further in accordance with an aspect of an embodiment of the invention, the traditional quadrature output signals are controlled using a simple finite state machine.

Still further in accordance with an aspect of an embodiment of the invention, the first transducer, the second transducer, the third transducer, and the fourth transducer are Hall-effect sensors.

Yet further in accordance with an aspect of an embodiment of the invention, the signal selection means, the signal normalizing means, the phase angle lookup means, the phase translation means, the phase register means, the phase subtractor means, the overflow corrector means, the traditional quadrature output emulating means and the simple finite state machine are implemented in software in a digital controller.

According to a second aspect of the invention, a method for sensing position and/or displacement of a moving ram, substrate or the like is provided in which multiple state changes are generated in two quadrature signals, such that the state changes correspond to discreet locations within the interval between two magnetic bands.

In accordance with this aspect of an embodiment of the invention, the ram is outfitted with a plurality of equally-spaced bands of magnetic material disposed circumferentially around the girth of the ram or placed as required or desired.

Further in accordance with this aspect of an embodiment of the invention, the method comprises the following steps: acquiring a first signal related to the position of the ram; acquiring a second signal related to the position of the ram that is 90 degrees out of phase with the first signal related to the position of the ram; comparing the first signal related to the position of the ram to the second signal related to the position of the ram, selecting the signal with the lesser instantaneous magnitude as the primary signal, selecting the signal with the greater instantaneous magnitude as the secondary signal, and producing a reference signal indicating whether the first signal related to the position of the ram or the second signal related to the position of the ram was selected as the primary signal; converting the primary signal into a phase angle signal; determining angular movement over time based on the value of the phase angle signal over time and creating an angular movement signal; and converting the angular movement signal into traditional quadrature output signals.

Still further in accordance with this aspect of an embodiment of the invention, converting the primary signal into a phase angle signal corresponding comprises the following steps: producing a normalized position signal by mapping the primary signal to a corresponding substantially sinusoidal signal with a known amplitude; converting the normalized position signal into an uncorrected phase angle signal corresponding to the instantaneous phase angle of the normalized position signal; and producing a phase angle signal by correcting the phase angle signal based on the values of the secondary signal and the reference signal.

Yet further in accordance with an aspect of an embodiment of the invention, determining angular movement over time and producing a corresponding angular movement output signal comprises the following steps: storing the phase angle signal and outputting a previous iteration phase angle output equal to the phase angle signal; subtracting the previous iteration phase angle signal from the phase angle signal and producing an uncorrected angular movement signal; and producing the angular movement signal by correcting the uncorrected angular movement signal in the case of an overflow or underflow.

Still further in accordance with an aspect of an embodiment of the invention, acquiring the first signal related to the position of the ram comprises using a first transducer and a second transducer mounted in close proximity to the ram such that when the ram moves the plurality of bands of magnetic material disposed circumferentially around the girth of the ram pass the transducers thereby generating a first transducer output signal and a second transducer output signal. Yet further in accordance with this aspect of the invention, the first transducer and the second transducer are positioned linearly with respect to each other and are spaced such that the distance between the first transducer and the second transducer is one-half of the distance between two adjacent bands of magnetic material disposed circumferentially around the girth of the ram such that the first transducer output signal is 180 degrees out of phase with the second transducer output signal.

Still further in accordance with an aspect of an embodiment of the invention, acquiring the second signal related to the position of the ram comprises using a third transducer and a fourth transducer mounted in close proximity to the ram such that when the ram moves the plurality of bands of magnetic material disposed circumferentially around the girth of the ram pass the transducers thereby generating a third transducer output signal and a fourth transducer output signal. Yet further in accordance with this aspect of the invention,

the third transducer and the fourth transducer are positioned linearly with respect to each

other and are spaced such that the distance between the third transducer and the fourth

transducer is one-half of the distance between two adjacent bands of magnetic material

disposed circumferentially around the girth of the ram. Consequently, the third transducer

output signal is 180 degrees out of phase with the fourth transducer output signal. Still

further in accordance with this aspect of the invention, the third transducer is located between

the first transducer and the second transducer, and the distance between the third transducer

and the first transducer and the third transducer and the second transducer is one-quarter of

the distance between two adjacent bands of magnetic material disposed circumferentially

around the girth of the ram. Still further in accordance with this invention, the distance

between the fourth transducer and the first transducer is three-quarters of the distance

between two adjacent bands of magnetic material disposed circumferentially around the girth

of the ram, and the distance between the fourth transducer and the second transducer is one-

quarter of the distance between two adjacent bands of magnetic material disposed

circumferentially around the girth of the ram.

Still further in accordance with an aspect of an embodiment of the invention,

acquiring the first signal related to the position of the ram further comprises the following

steps: producing a first combined signal by subtracting the second transducer output signal

from the first transducer output signal and amplifying the resulting signal; producing a first

digital error output signal; converting the first digital error output signal into a first analog

error signal; producing a first calibrated signal by subtracting the first analog error signal

from the first combined signal; and producing the first signal related to the position of the

ram by converting the first calibrated signal into a corresponding digital signal.

Yet further in accordance with an aspect of an embodiment of the invention, acquiring

the second signal related to the position of the ram comprises the following steps: producing

a second combined signal by subtracting the fourth transducer output signal from the third

transducer output signal and amplifying the resulting signal; producing a second digital error

output signal; converting the second digital error output signal into a second analog error

signal; producing a second calibrated signal by subtracting the second analog error signal

from the second combined signal; and producing the second signal related to the position of

the ram by converting the second calibrated signal into a corresponding digital signal.

Still further in accordance with an aspect of an embodiment of the invention, producing the first digital error signal comprises the following steps: performing a time-average of the first signal related to the position of the ram, and subtracting it from the value of the direct current offset required by the first analog-to-digital converter.

Yet further in accordance with an aspect of an embodiment of the invention, producing the second digital error signal comprises the following steps: performing a time-average of the second signal related to the position of the ram and subtracting it from the value of the direct current offset required by the second analog-to-digital converter.

While some of the embodiments discussed herein may rely on a ram or substrate to generate the sinusoidal signals, one of ordinary skill in the art will appreciate that these sinusoidal signals may be generated by other well-known means, such as by an optical encoder or the like. For example, and not limited thereto, the substrate/target of the system may be an optical encoder. The optical encoder may be an encoder wheel or the like. The optical encoder wheel may comprise apertures wherein when at least one of the first signal acquisition means and second signal acquisition means may be an optical detector. The optical detector may be a photo diode or the like.

These and other objects, along with advantages and features of the invention disclosed herein, will be made more apparent from the description, figures and claims that follow.

BRIEF SUMMARY OF THE DRAWINGS

The foregoing and other objects, features and advantages of the present invention, as well as the invention itself, will be more fully understood from the following description of preferred embodiments, when read together with the accompanying drawings in which:

FIG. 1 is a schematic diagram, showing a ram subject to axial movement, transducers for sensing movement of the ram, and the signal processing components of an embodiment of the present invention in block diagram form.

FIG 2. is a graphic representation of two input signals in quadrature.

FIG. 3 is a graphic representation of two input sinusoidal signals in quadrature, two conventional quadrature output signals corresponding to the two input sinusoidal signals in quadrature, and two enhanced resolution quadrature output signals corresponding to the two input signals sinusoidal signals in quadrature.

FIG 4. is a state diagram for a simple finite state machine used to generate traditional quadrature output signals.

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DETAILED DESCRIPTION OF THE INVENTION

Turning now to the drawings, **FIG. 1** shows a substrate such as a ram **10**, piston, target, optical encoder, or the like subject to axial movement. The ram **10** (i.e., piston, target, optical encoder, substrate or work piece) has equally-spaced bands **12** of magnetic material disposed circumferentially around its girth. In an embodiment, the bands of magnetic material **12** are spaced at intervals **14** that are 1/20th of an inch. However, one of ordinary skill in the art will appreciate that other intervals are possible.

Four transducers **16, 18, 20, 22,** are mounted in close proximity to the ram **10** such that when the ram **10** moves, the bands of magnetic material **12** pass the transducers **16, 18, 20, 22** thereby generating four sinusoidal transducer output signals **24, 26, 28, 30** related to the position and displacement of the ram **10**. The four transducers **16, 18, 20, 22** are spaced at precise distances with respect to one another such that the distance between the first transducer **16** and the second transducer **18** is one-fourth of the interval **14** between the bands of magnetic material **12** disposed circumferentially around the girth of the ram **10**; the distance between the second transducer **18** and the third transducer **20** is one-fourth of the interval **14** between the bands of magnetic material **12** disposed circumferentially around the girth of the ram **10**; and the distance between the third transducer **20** and the fourth transducer **22** is one-fourth of the interval **14** between the bands of magnetic material **12** disposed circumferentially around the girth of the ram **10**. Consequently, the first transducer output signal **24** is 90 degrees out of phase with the second transducer output signal **26**; 180 degrees out of phase with the third transducer output signal **28**; and 270 degrees out of phase with the fourth transducer output signal **30**. Thus, the four transducer output signals **24, 26, 28, 30** are defined by the following equations:

$$\text{first transducer output signal} = \cos\left(360^o \times \frac{position}{interval}\right) \tag{1}$$

$$\text{second transducer output signal} = \cos\left(360^o \times \frac{position}{interval} - 90^o\right) \tag{2}$$

$$\text{third transducer output signal} = \cos\left(360^{o} \times \frac{position}{interval} - 180^{o}\right) \qquad (3)$$

$$\text{fourth transducer output signal} = \cos\left(360^{o} \times \frac{position}{interval} - 270^{o}\right) \qquad (4)$$

In an embodiment, the four transducers **16, 18, 20, 22** are Hall-effect sensors. However, one of ordinary skill in the art will appreciate that other magnetic transducers could also be used.

The first transducer output signal **24** is applied to one terminal of the first signal combiner **32** and the third transducer output signal **28** is applied to the second terminal of the first signal combiner **32**. The output voltage for the first signal combiner **32** follows the equation:

$$\text{first combined signal} = gain \times (\text{first transducer output} - \text{third transducer output}) \qquad (5)$$

$$\text{first combined signal} = gain \times \left(\cos\left(360^{o} \times \frac{position}{interval}\right) - \cos\left(360^{o} \times \frac{position}{interval} - 180^{o}\right)\right) \qquad (6)$$

$$\text{first combined signal} = 2 \times gain \times \cos\left(360^{o} \times \frac{position}{interval}\right) \qquad (7)$$

In an embodiment, the first signal combiner **32** is a differential amplifier. However, one of ordinary skill in the art will appreciate that other components could be employed in place of a differential amplifier.

The second transducer output signal **24** is applied to one terminal of the second signal combiner **34** and the fourth transducer output signal **30** is applied to the second terminal of the second signal combiner **34**. The output voltage for the second signal combiner **34** follows the equation:

$$\text{second combined signal} = gain \times (\text{second transducer output} - \text{fourth transducer output}) \qquad (8)$$

$$\text{second combined signal} = gain \times \left(\cos\left(360^{o} \times \frac{position}{interval}\right) - \cos\left(360^{o} \times \frac{position}{interval} - 180^{o}\right)\right) \qquad (9)$$

$$\text{second combined signal} = 2 \times gain \times \sin\left(360^{o} \times \frac{position}{interval}\right) \qquad (10)$$

In an embodiment, the second signal combiner **34** is a differential amplifier. However, one of ordinary skill in the art will appreciate that other components could be employed in place of a differential amplifier.

Thus, the first combined signal **36** and the second combined signal **38** are dependent upon the position of the ram **10**. Moreover, the first combined signal **36** and the second combined signal **38** are approximately sinusoidal and vary through one sinusoidal period for each interval **14** of axial movement of the ram **10**. Representations of the first combined signal **36** and the second combined signal **38** over time are illustrated graphically in **FIG. 2**, having an x-axis in degrees and a y-axis amplitude in volts. As can be seen, the first combined signal **36** is sinusoidal. The second combined signal **38** is also sinusoidal but is 90 degrees out of phase with the first combined signal. In other words, the first combined signal and the second combined signal are in quadrature. While some of the embodiments discussed herein may rely on a ram or substrate to generate the sinusoidal signals, one of ordinary skill in the art will appreciate that these sinusoidal signals may be generated by other well-known means, such as by an optical encoder or the like. For example, and not limited thereto, the substrate/target of the system may be an optical encoder. The optical encoder may be an encoder wheel or the like. The optical encoder wheel may comprise apertures wherein when at least one of the first signal acquisition means and second signal acquisition means may be an optical detector. The optical detector may be a photo diode or the like.

After acquiring the first combined signal **36** and the second combined signal **38**, the invention performs a number of digital signal processing techniques on the two signals **36**, **38**. In an embodiment of this invention, the digital signal processing techniques are performed on the first combined signal **36** and the second combined signal **38** using a digital controller **39**. In particular, in an embodiment of this invention, the digital controller is a MSP430 Mixed Signal Processor manufactured by Texas Instruments. However, one of ordinary skill in the art will appreciate that the digital signal processing techniques could be accomplished using a wide variety of other components, including, but not limited to, other signal processing chips or digital controllers, field programmable gate arrays, or discrete circuit components.

Two analog-to-digital (A-D) converters **48**, **50** convert the first combined signal 36 and the second combined signal 38 into corresponding digital signals **52, 54**. In an embodiment of this invention, the two A-D converters **48, 50** are included on the MSP430 Mixed Signal Processor and require that the input signals have a direct current (DC) offset of 1.5 V. However, one of ordinary skill in the art will appreciate that different A-D converters

could be used in place of the A-D converters on the MSP430 Mixed Signal Processor and that such A-D converters might required different DC offsets.

The first combined signal **36** and the second combined signal **38** both have unpredictable DC offset components due to manufacturing tolerances, placement tolerances, variations in magnetic flux intensity, and other factors. In order to calibrate the first combined signal **36** and the second combined signal **38** such that they both exhibit the DC offset required by the two A-D converters **48**, **50**, two simple control loops **72**, **74** are used. In an embodiment of this invention, calibration is controlled by the MSP403 Mixed Signal Processor and is performed only when power is first applied to the system. However, one of ordinary skill in the art will appreciate that calibration could be achieved without relying on the MSP403 Mixed Signal Processor. Furthermore, one of ordinary skill in the art will also recognize that calibration could be performed continuously, periodically, or aperiodically during operation of the system.

The first control loop **72** used to calibrate the DC offset of the first combined signal **36**, consists of the first A-D converter **48**, the first averager **56**, the first digital-to-analog (D-A) converter **64**, and the first subtractor **40**. The first averager **56** generates a first digital error signal **60**. During calibration, the first digital error signal **60** is set to zero volts. The zero-volt first digital error signal **60** is then converted to a zero-volt first analog error signal **68** by the first D-A converter **64**. The first combined signal **36** and the first analog error signal **68** are then applied to the inputs of the first subtractor **40** and the first calibrated signal **44** is generated by subtracting the first analog error signal **68** from the first combined signal **36**. The first calibrated signal **44** thus follows the first combined signal **36** during calibration. The first calibrated signal **44** is then passed to the first A-D converter **48** and converted into the first sinusoidal signal **52** related to the position of the ram. The first averager **56** then performs a time-average of the first sinusoidal signal **52** related to the position of the ram over an interval of time equal to an integer multiple of one period of the first sinusoidal signal **52** related to the position of the ram. After calibration is complete, the first averager **56** sets the value of the first digital error signal **60** by subtracting the average value of the first sinusoidal signal **52** related to the position of the ram from the value of the DC offset required by the first A-D converter **48**:

first digital error signal = required DC offset – average of first signal related to position   (11)

The first digital error signal **60** is then converted into the corresponding first analog error signal **68** by the first D-A converter **64** and the first subtractor **40** removes the error component from subsequent analog values of the first combined signal **36**. Hereafter, the first calibrated signal **44** will have a precise DC offset equal to the DC offset required by the first A-D converter **48**.

The second combined signal **38** is calibrated to the appropriate DC offset by the same process as that used for the first combined signal **36**. The second control loop **74** used to calibrate the DC offset of the second combined signal **38**, consists of the second A-D converter **50**, the second averager **58**, the second digital-to-analog (D-A) converter **66**, and the second subtractor **42**. The second averager **58** generates a second digital error signal **62**. During calibration, the second digital error signal **62** is set to zero volts. The zero-volt second digital error signal **62** is then converted to a zero-volt second analog error signal **70** by the second D-A converter **66**. The second combined signal **38** and the second analog error signal **70** are then applied to the inputs of the second subtractor **42** and the second calibrated signal **46** is generated by subtracting the second analog error signal **70** from the second combined signal **38**. The second calibrated signal **46** thus follows the second combined signal **38** during calibration. The second calibrated signal **46** is then passed to the second A-D converter **50** and converted into the second sinusoidal signal **54** related to the position of the ram. The second averaging component **58** then performs a time-average of the second sinusoidal signal **54** related to the position of the ram over an interval of time equal to an integer multiple of one period of the second sinusoidal signal **54** related to the position of the ram. After calibration is complete, the second averaging component **58** sets the value of the second digital error signal **62** by subtracting the average value of the second sinusoidal signal **54** related to the position of the ram from the value of the DC offset required by the second A-D converter **50**:

second digital error signal = required DC offset − average of second signal related to position   (12)

The second digital error signal **62** is then converted into the corresponding second analog error signal **70** by the second D-A converter **66** and the second subtractor **42** removes the error component from subsequent analog values of the second combined signal **38**. Hereafter, the second calibrated signal **46** will have a precise DC offset equal to the DC offset required by the second A-D converter **50**.

As already disclosed, in an embodiment of this invention, the first A-D converter **48** and the second A-D converter **50** are included on the MSP430 Mixed Signal Processor. The A-D converters on the MSP430 Mixed Signal Processor convert analog signals within the range of 0 V – 3 V to 12-bit signed integer values within the range -2048 – 2047. In an

5   embodiment, after calibration and conversion, both the first sinusoidal signal **52** related to the position of the ram and the second sinusoidal signal **54** related to the position of the ram are centered in the middle of the 12-bit sampling window at a DC offset of zero.

After conversion, the first sinusoidal signal **52** related to the position of the ram and the second sinusoidal signal **54** related to the position of the ram are passed to a signal

0   selection component **76**. The signal selection component 76 compares the instantaneous magnitude of the first sinusoidal signal **52** related to the position of the ram to the instantaneous magnitude of the second sinusoidal signal related to the position of the ram and selects the signal with the lesser instantaneous magnitude as the primary signal **78** and the signal with the greater instantaneous magnitude as the secondary signal **80**. The signal

5   selection component **76** also produces as an output a reference signal **82** indicating whether the signal selection component **76** selected the first sinusoidal signal **52** related to the position of the ram or the second sinusoidal signal **54** related to the position of the ram as the primary signal **78**. In an embodiment of this invention, the reference signal **82** is set to 0 when the first sinusoidal signal **52** related to the position of the ram is selected as the primary signal **78**

0   and the reference signal **82** is set to 1 when the second sinusoidal signal **54** related to the position of the ram is selected as the primary signal **78**.

After one signal has been selected as the primary signal **78**, the normalization component **84** converts the primary signal **78** into the normalized position signal **86** by normalizing the primary signal **78**. That is, the normalization component **84** maps the

5   primary signal **78** with unknown amplitude to a corresponding sinusoidal signal with a known amplitude.

The first step required to normalize the primary signal **78** is to estimate the amplitude of the primary signal **78**. This is accomplished by taking advantage of the relationship between the primary signal **78** and the secondary signal **80**. The primary signal **78** and the

)   secondary signal **80** were derived from the first calibrated signal **44** and the second calibrated signal **46** and therefore both have the same amplitude and the same frequency. Furthermore, the primary signal **78** and the secondary signal **80** are 90 degrees out of phase. That is, if the

first sinusoidal signal **52** related to the position of the ram was selected as the primary signal **78**, the primary signal **78** and the secondary signal **80** have the form $\text{amplitude} \times \cos(x)$ and $\text{amplitude} \times \sin(x)$ respectively. On the other hand, if the second sinusoidal signal **54** related to the position of the ram was selected as the primary signal **78**, the primary signal **78** and the secondary signal **80** have the form $\text{amplitude} \times \sin(x)$ and $\text{amplitude} \times \cos(x)$ respectively. Thus, according to the geometric identity $\sin^2(x) + \cos^2(x) = 1$:

$$\sqrt{p^2 + s^2} = \sqrt{\text{amplitude}^2 \times \left(\cos^2(x) + \sin^2(x)\right)} = \text{amplitude} \tag{13}$$

$$\text{amplitude} = \sqrt{p^2 + s^2} \tag{14}$$

where "p" represents the instantaneous magnitude of the primary signal **78** and "s" represents the instantaneous magnitude of the secondary signal **80**. Therefore, it is possible to estimate the amplitude of the primary signal **78** by taking the square root of the sum of the square of the instantaneous amplitude of the primary signal **78** and the square of the instantaneous amplitude of the secondary signal **80**.

After $p^2 + s^2$ has been calculated, an embodiment of this invention utilizes a lookup table to bypass the costly digital square-root operation required by equation (14). In an embodiment of this invention, only 11-bit amplitudes are meaningful because, as disclosed before, both the primary signal **78** and the secondary signal **80** are 12-bit signed integers. Accordingly, the maximum amplitude of the primary signal **78** is 2048. Elements in the lookup table are stored in read-only memory with addresses 1, 2, ... 2048 and the value stored in each memory address equals the square of that address. For example, the value stored at address 4 is 16, and the value stored at address 5 is 25. In order to determine the square root of the sum, the normalizing component performs a binary search of the lookup table until the sum is located. Once the value of the sum is located in the lookup table, the square root of the sum is known because the memory address of each element in the lookup table corresponds to the square root of the value stored in that memory address. Due to the fact that in an embodiment of the invention there are only 2048 entries in the lookup table the costly digital square-root operation is reduced to a simple 11-step binary search.

After estimating the amplitude of the primary signal **78**, the final step required to normalize the primary signal **78** is to scale the primary signal **78**. The normalization

component **84** scales the primary signal **78** to the desired known amplitude according to the following equation:

$$\text{normalized position signal} = \frac{\text{known amplitude} \times p}{\text{amplitude}} \tag{15}$$

In order to eliminate the costly division required by equation (15), a second lookup table is utilized in an embodiment of the invention.

Elements in the lookup table are stored in read-only memory with addresses 1, 2, ... 2048, with each address corresponding to one possible value for the amplitude of the primary signal **78**. The value stored at each memory address is equal to:

$$value = \left\lfloor \frac{\text{known amplitude}}{address} \times 2^{10} \right\rfloor \tag{16}$$

where $\lfloor \ \rfloor$ represents the floor (or round down) operation.

The first step in scaling the primary signal **78**, therefore, is to obtain the value stored in the memory address of the lookup table that corresponds to the estimated value of the amplitude of the primary signal **78**. After retrieving this value from the lookup table, it is multiplied by the instantaneous value of the primary signal **78**. Finally, in order to compensate for the multiplication by 2^{10} in equation (16), it is necessary to divide the result by 2^{10}. In an embodiment of this invention, this division is accomplished by shifting the result right by ten bits. (The right shift operation is a fast digital technique for dividing by 2^{10}.) Therefore, the process of scaling the primary signal **78** is summarized by the following equation:

$$\text{normalized position signal} = \left\lfloor \frac{\text{known amplitude}}{\text{amplitude}} \times 2^{10} \right\rfloor \times p \times 2^{-10} \approx \frac{\text{known amplitude} \times p}{\text{amplitude}} \tag{17}$$

In an embodiment of this invention, the normalization component 84 is implemented in software within the MSP430 Mixed Signal Processor. However, one of ordinary skill in the art will appreciate that the normalization component 84 could be implemented by a variety of other means including as a separate external component.

After normalizing the primary signal, the normalized position signal **86** is converted into a phase angle signal **94**. The value of the phase angle signal **94** represents the value of the phase angle of the normalized position signal **86** resolved to within a predefined subinterval within the range [0, 360 degrees]. In other words, the phase angle signal **94** does not represent the precise value of the phase angle of the normalized position signal **86**.

Rather, the phase angle signal **94** indicates that the precise value of the phase angle of the normalized position signal **86** falls within a particular subinterval within the range [0, 360 degrees]. The ultimate resolution of the system depends on the number of predefined subintervals within the range [0, 360 degrees]. In an embodiment of the invention, 32

5   subintervals are utilized. Consequently, in an embodiment of the invention, each subinterval spans a range of 11.25 degrees and the phase angle signal **94** indicates whether the precise phase angle of the normalized position signal **86** falls within the subinterval [0, 11.25 degrees], [11.25, 22.50 degrees], [22.50 degrees, 33.75 degrees], [33.75 degrees, 45.0 degrees], [45.0 degrees, 56.25 degrees], [56.25 degrees, 67.50 degrees], [67.50, 78.75

0   degrees], [78.75, 90 degrees], [90.0, 101.25 degrees], [101.25, 112.50 degrees], [112.05, 123.75 degrees], [123.75, 135.0 degrees], [135.0, 146.25 degrees], [146.25, 157.50 degrees], [157.50, 168.75 degrees], [168.75, 180.0 degrees], [180.0, 191.25 degrees], [191.25, 202.50 degrees], [202.50, 213.75 degrees], [213.75, 225.0 degrees], [225.0, 236.25 degrees], [236.25, 247.50 degrees], [247.50, 258.75 degrees], [258.75, 270.0 degrees], [270.0, 281.25

5   degrees], [281.25, 292.50 degrees], [292.50, 303.75], [303.75, 315.0 degrees], [315.0, 326.25 degrees], [326.25, 337.50 degrees], [337.50, 348.75 degrees], or [348.75, 360.0 degrees].

In order to resolve the phase angle of the normalized position signal **86** into the appropriate subinterval, the normalized position signal **86** is passed to the phase angle lookup component **88**. The phase angle lookup component **88** resolves the value of the phase angle

0   of the normalized position signal **86** to within the appropriate subinterval within the range [0, 180 degrees] and converts the normalized position signal **86** into the uncorrected phase angle signal **90**. The value of the uncorrected phase signal **90** indicates within which subinterval the precise value of the phase angle of the normalized position signal **86** falls. The phase angle lookup component **88** accomplishes this conversion according to the following

5   formula:

$$\text{uncorrected phase angle} = \left\lfloor \frac{resolution}{360°} \times \arccos\left(\frac{\text{normalized position signal}}{\text{known amplitude}} \right) \right\rfloor \quad (18)$$

where the value of resolution is the number of subintervals within the range [0, 360 degrees]. The domain of the arccosine function is [-1, 1]. Division of the normalized position signal **86** by the known amplitude of the normalized position signal **86** is required to map the

ι   instantaneous value of the normalized position signal **86** which, in an embodiment of this invention can vary from [-2048, 2047], to the required [-1, 1] domain. Multiplication of the

result of the arccosine operation by the constant term (resolution/360 degrees) and the subsequent floor operation maps the result of the arccosine operation onto the integer interval [0, (resolution/2) – 1].

The arccosine operation and the division operation are both complicated digital operations. Accordingly, an embodiment of this invention utilizes a lookup table to bypass these costly operations. As disclosed previously, in an embodiment of this invention, the amplitude of the normalized position signal **86** is 2048. In other words, the value of the normalized position signal **86** varies over the interval [-2048, 2047]. Therefore, the lookup table stores elements in read-only memory with addresses -2048, -2047, ... , 2046, 2047 corresponding to all possible values of the normalized position signal 86 and the value stored at each memory address of the lookup table is equal to the value of the uncorrected phase angle signal **90** corresponding to the value of the normalized position signal **86** as defined in equation (18) above. Consequently, the costly digital operations required to calculate the value of the uncorrected phase signal **90** are reduced to a simple memory retrieval operation. In an embodiment of this invention, the phase angle lookup component **88** is implemented in software within the MSP430 Mixed Signal Processor. However, one of ordinary skill in the art will appreciate that the phase angle converter **88** could be implemented by a variety of other means including as a separate external component.

Due to the fact that the range of the arccosine function is [0, 180 degrees], the phase angle lookup component **88** only resolves the value of the phase angle of the normalized position signal **86** to a value within the range [0, (resolution/2) – 1] corresponding to a particular subinterval within the range [0, 180 degrees]. Therefore, in order to resolve the value of the phase angle of the normalized position signal **86** into a value within the range [0. resolution – 1] corresponding to a particular subinterval within the range [0, 360 degrees], the uncorrected phase angle signal **90** is passed to the phase translator **92**. The phase translator **92** resolves the value of the phase angle of the normalized position signal **86** into the appropriate subinterval within the range [0, 360 degrees] and converts the uncorrected phase angle signal **90** into the phase angle signal **94**. In addition, in the case that the uncorrected phase angle signal **90** was derived from the second combined signal **38**, a sinusoidal signal that is 90 degrees ahead of the first combined signal **36**, the phase translator **92** shifts the resulting phase angle signal 90 degrees forward.

In addition to receiving the uncorrected phase angle signal **90**, the phase translator **92** also receives the reference signal **82** and the secondary signal **80**. If the reference signal **82** indicates that the first sinusoidal signal **52** related to the position of the ram was selected as the primary signal **78**, the phase translator **92** only resolves the value of the phase angle of the normalized position signal **86** into the appropriate subinterval within the range [0, 360 degrees]. The phase translator **92** determines what corrections are required by inspecting the sign of the secondary signal **80** (i.e., the second sinusoidal signal **54** related to the position of the ram). If the value of the secondary signal **80** is greater than zero, then the uncorrected phase angle signal **90** is correctly situated in the interval [0, 180 degrees]. Thus, if the sign of the secondary signal **80** is greater than zero, the phase angle signal **94** is defined by the equation:

$$\text{phase angle signal} = \text{uncorrected phase angle signal} \qquad \qquad (19)$$

If the value of the secondary signal **80** is less than zero, then the uncorrected phase angle signal **90** must be shifted to be in the interval [180, 360 degrees]. This correction is performed according to the following equation:

$$\text{phase angle signal} = \text{resolution} - 1 - \text{uncorrected phase angle signal} \qquad (20)$$

If the reference signal **82** indicates that the second sinusoidal signal **54** related to the position of the ram was selected as the primary signal **78**, the phase translator **92** resolves the value of the phase angle of the normalized position signal **86** into the appropriate subinterval within the range [0, 360 degrees] and also shifts the result forward 90 degrees. The phase translator **92** determines what corrections are required by inspecting the sign of the secondary signal **80** (i.e., the first sinusoidal signal **52** related to the position of the ram). If the value of the secondary signal **80** is less than zero, then the uncorrected phase angle signal **90** is correctly situated in the interval [0, 180 degrees] and only the 90-degree forward shift correction is required. Thus, if the value of the secondary signal **80** is less than zero, the value of the phase angle signal **94** is defined by the equation:

$$\text{phase angle signal} = \left(\text{uncorrected phase angle signal} + \frac{\text{resolution}}{4} \right) \% \text{ resolution} \quad (21)$$

where the % symbol represents modulo division. If the value of the secondary signal is greater than zero, then the value of the uncorrected phase angle signal **90** must be mapped into the interval [180, 360 degrees] and the result must be shifted forward 90 degrees. Thus,

if the value of the secondary signal **80** is greater than zero, the value of the phase angle signal **94** is defined by the equation:

$$\text{phase angle signal} = \left((\text{resolution} - 1 - \text{uncorrected phase angle signal}) + \frac{\text{resolution}}{4} \right) \% \text{ resolution} \quad (22)$$

The phase angle signal **94** therefore represents an unsigned integer between the range [0, resolution −1]. In an embodiment of this invention, the phase translator **92** is implemented in software within the MSP430 Mixed Signal Processor. However, one of ordinary skill in the art will appreciate that the phase translator **92** could be implemented by a variety of other means including as a separate external component.

Angular displacement is determined by monitoring the change in value of the phase angle signal **94** over time. Accordingly, the phase angle signal **94** is sent to both the phase register **96** and the phase subtractor **100**. The phase register stores the value of the phase angle signal **94** for one sensing iteration and then produces a previous iteration phase angle signal **98** equal to the stored value of the phase angle signal **94**. In other words, the phase register **96** holds the value of the phase angle signal **94** from the previous iteration.

The phase subtractor **100** receives both the phase angle signal **94** and the previous iteration phase angle signal **98** and determines the amount of angular movement that occurred during the current iteration by subtracting the value of the previous iteration phase angle signal **98** from the value of the phase angle signal **94**. In other words, the amount of angular movement during one sensing iteration is simply the difference between the value of the phase angle signal **94** and the previous iteration phase angle signal **98**. Thus, the output of the phase subtractor **100**, the uncorrected angular movement signal **102**, is defined by the equation:

$$uncorrected\ angular\ movement\ signal = phase\ angle\ signal - previous\ iteration\ phase\ angle\ signal \quad (23)$$

In an embodiment of this invention, the phase register **96** and the phase subtractor **100** are implemented in software within the MSP430 Mixed Signal Processor. However, one of ordinary skill in the art will appreciate that the phase register **96** and the phase subtractor **100** could be implemented by a variety of other means including as a separate external component.

Depending on the amount of angular movement during a particular iteration, the system might experience overflow or underflow. Overflow occurs when the phase angle transitions from 359 degrees to 0 degrees. In such a situation, the system will recognize an apparent angular movement of -359 degrees when only 1 degrees of actual angular movement has occurred. Similarly, underflow occurs when the phase angle transitions from 0 degrees to 359 degrees. In such a situation, the system will recognize an apparent angular movement of 359 degrees when only -1 degrees of actual angular movement has occurred. The overflow corrector **104** compensates for any overflow or underflow reflected in the uncorrected angular movement signal (UAMS) **102** and produces an output signal, the angular movement signal (AMS) **106**, defined by the following equation:

$$AMS = \begin{cases} UAMS - resolution & , \text{if } UAMS > \text{resolution}/2 \\ UAMS + resolution & , \text{if } UAMS < -\text{resolution}/2 \\ UAMS & , \text{else} \end{cases} \quad (24)$$

In an embodiment of this invention, the overflow corrector **104** is implemented in software within the MSP430 Mixed Signal Processor. However, one of ordinary skill in the art will appreciate that the overflow corrector could be implemented by a variety of other means including as a separate external component.

The angular movement signal **106** is meaningless to most traditional decoders. In order to interface the invention with a traditional decoder, it is necessary for the invention to produce output signals that resemble traditional quadrature output signals. Therefore, the traditional quadrature output emulator **108** is used to convert the angular movement signal **106** into traditional quadrature output signals, lead output signal **110** and trail output signal **112**. Traditional quadrature output signals are generally pulse trains generated by passing two sinusoidal signals in quadrature through zero crossing detectors.

FIGS. 3(A)-(C) graphically illustrate the relationship between two traditional quadrature output signals **204, 206** and the sinusoidal signals **200, 202** in quadrature from which the two traditional quadrature output signals **204, 206** were generated. As shown in FIGS. 3(A) and 3(B), the first quadrature output signal **204** corresponds to the first sinusoidal signal **200**. The first quadrature output signal **204** changes state twice, once for each time the first sinusoidal signal **200** crosses zero. As shown in FIGS. 3(A) and 3(C), the second quadrature output signal **206** corresponds to the second sinusoidal signal **202**. Similarly, the

second quadrature output signal **206** changes state twice, once for each time the second sinusoidal signal **202** crosses zero. Consequently, the two quadrature output signals **204, 206** collectively experience four state changes over one period (i.e., 11, 01, 00, 10).

The traditional quadrature output emulator **108** (previously discussed in **FIG. 1**) generates the lead output signal **110** and trail output signal **112**. Similar to the first quadrature output signal **204** and the second quadrature output signal **206**, the lead output signal **110** and the trail output signal **112** are periodic pulse trains with equal frequencies, as shown in **FIGS. 3(D)** and **3(E)**. Moreover, just as the first quadrature output signal **204** trails the second quadrature output signal **206** by 90 degrees, the lead output signal **110** trails the trail output signal **112** by 90 degrees. In an embodiment of this invention, a simple finite state machine controls the lead and trail signals based on the value of the angular movement signal **106**. Turning to **FIG. 4**, **FIG. 4** schematically depicts a state diagram for the simple finite state machine **300** representing the output emulator. The simple state machine has four states **301, 302, 304, 306**. The first state **301** corresponds to when the lead output signal **110** equals one and the trail output signal **112** equals one. The second state **302** corresponds to when the lead output signal **110** equals zero and the trail output signal **112** equals one. The third state **304** corresponds to when the lead output signal **110** equals zero and the trail output signal **112** equals zero. The fourth state corresponds to when the lead output signal **110** equals one and the trail output signal equals zero. It should be noted that these states correspond to the same progression of states discussed in connection with the first quadrature output signal **204** and the second quadrature output signal **206**.

The traditional quadrature output emulating means **108** uses the value of the angular movement signal **106** to determine how many transitions to follow along the state machine. If the value of the angular movement signal **106** is positive for one sensing iteration, the traditional quadrature output emulator **108** will follow "forward" transitions along the state machine. Similarly, if the value of the angular movement signal **106** is negative for one sensing iteration, the traditional quadrature output emulating means 108 will follow "backward" transitions along the state machine. For example, if the value of the angular movement signal **106** equals 3 for one sensing iteration, and the traditional quadrature output emulator **108** stopped at the first state **301** after the last sensing iteration, the traditional quadrature output emulator **108** will start at the first state **301**, and transition forward three states through the second state **302**, the third state **304**, and the fourth state **306**.

Consequently, for this sensing iteration, the traditional quadrature output emulator 108 will toggle the lead output signal 110 and the trail output signal 112 through the following progression: lead output signal = 0, trail output signal = 1; lead output signal = 0, trail output signal = 0; and lead output signal = 1 and trail output signal = 0.

5   As disclosed above, in an embodiment of the invention, the value of the phase angle of the normalized position signal 86 is resolved to within one of thirty-two subintervals within the range [0. 360 degrees]. Accordingly, for each period of the normalized position signal 86, the traditional quadrature output emulating means 108 will generate 32 state changes collectively in the lead output signal 110 and the trail output signal 112. Turning to

0   FIG. 2, the enhanced resolution provided by an embodiment of the invention is evident from a comparison of the waveforms of the lead output signal 110 and the trail output signal 112 and the waveforms of the first quadrature output signal 204 and the second quadrature output signal 206. For each period of the first quadrature output signal 204 and the second quadrature output signal 206, the lead output signal 110 and the trail output signal experience

5   eight periods. Thus, the resolution of an embodiment of the invention is eight times that of a traditional quadrature sensor and 32 times the resolution of the underlying bands of magnetic material 12.

In an embodiment of this invention, in addition to generating and controlling the lead output signal 110 and the trail output signal 112, the traditional quadrature output emulator

0   108 also produces a valid output signal 114. After the traditional quadrature output emulator 108 has finished toggling the lead output signal 110 and the trail output signal 112 for each sensing iteration, the traditional quadrature output emulator 108 raises the valid signal 114 to high and then returns the valid signal 114 back to zero. The valid signal 114 is used to indicate to decoding logic that the output signaling for the sensing iteration has finished.

5   In an embodiment of this invention, the traditional quadrature output emulator 108 is implemented in software within the MSP430 Mixed Signal Processor. However, one of ordinary skill in the art will appreciate that the traditional quadrature output emulator 108 could be implemented in a variety of different ways including as a separate external component.

)   Still other embodiments will become readily apparent to those skilled in this art from reading the above-recited detailed description and figures of certain exemplary embodiments. It should be understood that numerous variations, modifications, and additional embodiments

are possible, and accordingly, all such variations, modifications, sizes, levels, and embodiments are to be regarded as being within the spirit and scope of this document. For example, the above-recited detailed description discloses both a method and system for acquiring two substantially sinusoidal signals in quadrature and a method and system for

5   processing the two substantially sinusoidal signals. It will be appreciated by one of ordinary skill in the art that the method and system for processing two substantially sinusoidal signals disclosed in the above-recited detailed description is not limited to being used in conjunction with the method and system for acquiring two substantially sinusoidal signals in quadrature. That is, the method and system for processing two substantially sinusoidal signals disclosed

0   could be applied to any sensor that generates input signals in quadrature. For instance, the method and system for processing two substantially sinusoidal signals disclosed could also be used in conjunction with optical rotary encoders.

The various embodiments of the present invention system and method may be utilized for a variety of substrates (e.g., rams, encoder wheels or the like), functions, purposes,

5   methods and systems including as discussed in the following patents and publications listed below and of which are hereby incorporated by reference herein in their entirety:

U.S. Patent No. 6,630,659 B1 to Stridsberg, entitled "Position Transducer";

U.S. Patent No. 6,573,710 B1 to Santos et al., entitled "Position and/or Displacement Sensor Including a Plurality of Aligned Sensor Elements";

ɔ   U.S. Patent No. 6,556,153 B1 to Cardamone, entitled "System and Method for Improving Encoder Resolution";

U.S. Patent No. 6,459,261 B1 to Luetzow et al., entitled "Magnetic Incremental Motion Detection System and Method";

U.S. Patent No. 6,456,063 B1 to Moreno et al., entitled "Self Compensating Control

ͻ   Circuit for Digital Magnetic Sensors";

U.S. Patent No. 6,294,910 B1 to Travostino et al., entitled "Digital Position Sensor for Sensing Position of a Moving Target";

U.S. Patent No. 6,232,739 B1 to Krefta et al., entitled "High-Resolution Incremental Position Sensor With Pulse Switching Strategy";

ا   U.S. Patent No. 6,191,415 B1 to Stridsberg, entitled "Position Transducer";

U.S. Patent No. 6,172,359 B1 to Stridsberg, entitled "Position Transducer";

U.S. Patent No. 6,084,234 to Stridsberg, entitled "Position Transducer";

U.S. Patent No. 5,719,789 to Kawamata, entitled "Method of and Apparatus for Detecting an Amount of Displacement";

U.S. Patent No. 5,442,313 to Santos et al., entitled "Resolution Multiplying Circuit";

U.S. Patent No. 5,067,089 to Ishii et al., entitled "Device Having Signal Interpolation Circuit and Displacement Measuring Apparatus Comprising the Device";

U.S. Patent No. 5,041,784 to Griebeler, entitled "Magnetic Sensor With Rectangular Field Distorting Flux Bar";

U.S. Patent No. 5,012,239 to Griebeler, entitled "High Resolution Position Sensor Circuit";

U.S. Patent No. 4,972,080 to Taniguchi, entitled "Signal Processing Apparatus for Pulse Encoder With A/D Conversion and Clocking";

U.S. Patent No. 4,630,928 to Klingler et al., entitled "Length Measuring Device";

U.S. Patent No. 4,587,485 to Papiernik, entitled "Evaluation Arrangement for a Digital Incremental Transmitter";

U.S. Patent No. 3,956,973 to Pomplas, entitled "Die Casting Machine With Piston Positioning Control;" and

Z. Buckner, "Enhanced Resolution Quadrature Encoder Interface," master's thesis, Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, 2004.

Still other embodiments will become readily apparent to those skilled in this art from reading the above-recited detailed description and drawings of certain exemplary embodiments. It should be understood that numerous variations, modifications, and additional embodiments are possible, and accordingly, all such variations, modifications, and embodiments are to be regarded as being within the spirit and scope of the appended claims. For example, regardless of the content of any portion (e.g., title, section, abstract, drawing figure, etc.) of this application, unless clearly specified to the contrary, there is no requirement for any particular described or illustrated activity or element, any particular sequence of such activities, any particular size, speed, material, dimension, time period, or frequency, or any particular interrelationship of such elements. Moreover, any activity can be repeated, any activity can be performed by multiple entities, and/or any element can be duplicated. Further, any activity or element can be excluded, the sequence of activities can

vary, and/or the interrelationship of elements can vary. Accordingly, the descriptions and drawings are to be regarded as illustrative in nature, and not as restrictive.

The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The foregoing embodiments are therefore to be
5   considered in all respects illustrative rather than limiting of the invention described herein.